

**\*\*Volume Title\*\***

*ASP Conference Series, Vol. \*\*Volume Number\*\**

**\*\*Author\*\***

© **\*\*Copyright Year\*\*** *Astronomical Society of the Pacific*

## **A Tale of Two Stars: Interferometric Studies of Post-AGB Binaries**

M. Hillen<sup>1</sup>, J. Menu<sup>1</sup>, B. de Vries<sup>2</sup>, H. Van Winckel<sup>1</sup>, M. Min<sup>3</sup>, G.D. Mulders<sup>4</sup>,  
C. Gielen<sup>5</sup>, T. Wevers<sup>6</sup>, S. Regibo<sup>1</sup>, and T. Verhoelst<sup>5</sup>

<sup>1</sup>*Instituut voor Sterrenkunde, University of Leuven, Leuven, Belgium*

<sup>2</sup>*Department of Astronomy, AlbaNova University Center, Stockholm University, Stockholm, Sweden*

<sup>3</sup>*Sterrenkundig Instituut Anton Pannekoek, University of Amsterdam, Amsterdam, The Netherlands*

<sup>4</sup>*Lunar and Planetary Laboratory, The University of Arizona, Tucson AZ, USA*

<sup>5</sup>*Belgian Institute for Space Aeronomy, Brussels, Belgium*

<sup>6</sup>*Department of Astrophysics/IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands*

**Abstract.** Binaries with circumbinary disks are commonly found among optically bright post-AGB stars. Although clearly linked to binary interaction processes, the formation, evolution and fate of these disks are still badly understood. Due to their compactness, interferometric techniques are required to resolve them. Here, we discuss our high-quality multiwavelength interferometric data of two prototypical yet very different post-AGB binaries, AC and 89 Herculis, as well as the modeling thereof with radiative transfer models. A detailed account of the data and models of both objects is published in three separate papers elsewhere; here we focus on comparing the modeling results for the two objects. In particular we discuss the successes and limitations of the models which were developed for protoplanetary disks around young stars. We conclude that multiwavelength high-angular-resolution observations and radiative transfer disk models are indispensable to understand these complex interacting objects and their place in the grand scheme of the (binary) evolution of low and intermediate mass stars.

### **1. Introduction**

Based on recent surveys of the optically-bright post-AGB population in the Magellanic Clouds (MCs) (van Aarle et al. 2011; Kamath et al. 2014, see also D. Kamath's contribution in these proceedings), the formation of disks around post-AGB binaries seems to be a common process. Indeed, in analogy with the Galactic post-AGB stars with confirmed disks, about 40% of the optically bright post-AGB stars in the MCs have similar observational characteristics (i.e. a comparable IR excess and photospheric depletion pattern). Binary interaction is clearly a key ingredient in the formation of these disks, since in the Galaxy such stable structures are only found around post-AGB stars in binary systems of typically 1 AU in separation ( $P_{\text{orb}} \sim 100 - 3000$  d). The advantage of studying post-AGB stars in the MCs is that their distances, and hence luminosi-

ties, are well constrained, which is not the case for a typical Galactic source. On the other hand, to constrain the structure and evolution of the circumstellar environment in greater detail, one can better study the Galactic objects which can be spatially resolved with high-angular-resolution techniques. Here we focus on the results obtained in our recent studies of this kind. The long-term goals of this research are to further binary evolution theory by

- empirically constraining uncertain binary interaction processes related to the formation of these elusive disks,
- connecting the post-AGB binaries to other objects and evolutionary channels in the “binary zoo,” in search of their progenitors and progeny,

but also to study disk evolution in itself, since these objects

- form an ideal laboratory to study dust coagulation in a semi-stable environment,
- offer a unique region of parameter space to study mechanisms that are relevant for the formation of (circumbinary) planets.

## 2. The Two Stars: the Prototypes in Hercules

Two post-AGB systems were selected for a detailed study of the structure of their circumstellar environment, 89 Herculis (published as Hillen et al. 2013, 2014) and AC Herculis (Hillen et al., in prep.). Both systems are among the brightest and closest post-AGB binaries and have a long history as being recognised as likely disk objects. Waters et al. (1993) postulated 89 Her to have a disk, based on their evidence for the binary nature of the central object and the observed characteristics of the circumstellar environment (i.e. the stability of the IR excess, the CO(1-0) line profile, etc.). Similarly, Van Winckel et al. (1998) concluded, based on the close resemblance of AC Her with the Red Rectangle (i.e., the dust mineralogy, CO rotational line emission, mm continuum flux, etc.), that the circumstellar dust and gas in this system must also be in the form of a circumbinary disk. Simple radiative transfer disk models have already been computed for AC Her, in combination with a mineralogical study of the mid-IR emission features, by (Gielen et al. 2007). Here we compare our results for the two systems.

## 3. Our Tools

### 3.1. Observations: Optical Interferometry Combined with the SED

Extensive high-quality data sets were gathered for the two objects under study. For both systems the spectral energy distribution (SED) was constructed with a wide variety of photometric data from the literature, combined with new photometry collected with the SPIRE instrument onboard the *Herschel* satellite (Swinyard & et al. 2010; Pilbratt et al. 2010), as well as with the archival ISO spectra.

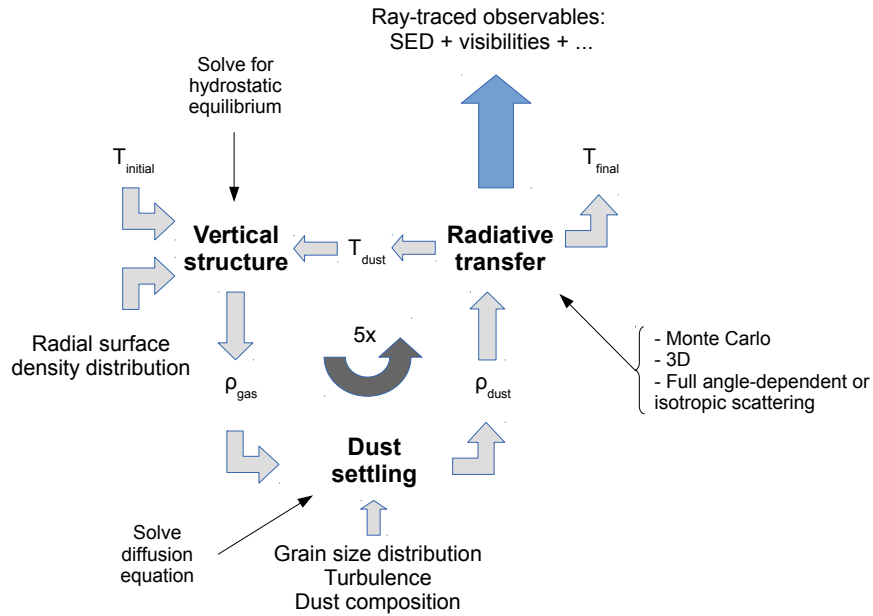
For 89 Her, we collected multiwavelength interferometric data, with currently operational interferometers (the VLTI, the CHARA Array and the NPOI) and from the archives of the PTI and the IOTA, that cover the optical, near-IR and mid-IR wavelength domains. In the case of AC Her, only three visibility spectra were acquired

with the MIDI instrument on the VLTI, but they are of very high quality and spatial resolution.

### 3.2. Radiative Transfer Disk Models

The main modeling tool used in our work is the MCMax radiative transfer code (Min et al. 2009). Being developed to model the effects of radiation transport through the optically thick media in protoplanetary disks on dust-related observables, MCMax can be very well applied to the circumstellar environments of evolved stars as well, and in particular to the disks around post-AGB binaries. The radiative transfer in MCMax is performed with a Monte Carlo method. The code, moreover, computes the vertical structure of the disk, by solving the equation of hydrostatic equilibrium. Finally, a grain size distribution can be included in the model, in combination with size-dependent dust settling to the disk midplane (i.e. turbulence vs. gravity, included in the form of a diffusion equation). An important assumption in the modeling is the way the radial surface density distribution is parameterized, which is typically in the form of a power law (with index -1 for protoplanetary disks). Figure 1 summarizes in the form of a diagram the iterative processes implemented in MCMax to arrive at a final disk structure and model predictions for observables (for more details, see Hillen et al. 2014; Mulders & Dominik 2012; Min et al. 2009, and references therein). In particular, the inclusion of mm-sized grains that are settled to the midplane of the disk is a great improvement with respect to previous radiative transfer models applied to post-AGB disks.

Figure 1. A diagram explaining the iterative sequence executed in the MCMax code which leads to the final disk structure.



#### 4. Modeling Results: Comparing the Two Stars

Extensive model grids were computed to explore the relevant parameter space. Due to the complexity of these stable, passive structures, there are many parameters involved in the structure computation, in addition to the geometric parameters like inclination and disk orientation on the sky (see Table 1). Not all parameters can be independently constrained based on the SED and interferometric data at near- to mid-IR wavelengths only. Therefore, we assumed certain values for specific parameters. These assumptions are different for the two systems, complicating a quantitative comparison between the resulting values for the fitted parameters. Nonetheless, several conclusions can be drawn with respect to the parameters that *are* well determined and concerning the validity of certain assumptions/parameterizations.

Table 1. Parameters of the best-fit MCMax radiative transfer disk models of 89 Her and AC Her. (F) means that the parameter was fixed to the given value.

Parameter	Best 89 Her	Best AC Her
$M_{\text{dust}} (M_{\odot})$	$5 \times 10^{-4}$	$2.5 \times 10^{-3}$
gas/dust	100 (F)	1 or 10
$a_{\text{min}}$	0.01 (F)	0.01 (F)
$a_{\text{max}}$ (mm)	10.0 (F)	1.0
$q$	-3.00	-3.25
$R_{\text{in}}$ (AU)	3.75	34.0
$R_{\text{out}}$	50 (F)	200 (F)
$R_{\text{mid}}/R_{\text{in}}$	3.0	2.0
$p_{\text{in}}$	-3.0	-3.0
$p_{\text{out}}$	1.5	1.0 (F)
$\alpha$	0.01 (F)	0.01 (F)
$i$ ( $^{\circ}$ )	13 (F)	50

First, it is striking that both systems require a surface density parameterization of two joined power laws to explain the data. The interferometric data (in the near-IR for 89 Her and in the mid-IR for AC Her) require a smoother intensity distribution than can be provided with a single power-law model (see Hillen et al. 2014, for a detailed discussion). Second, it is apparent that in both systems the grain size distribution power-law index is larger than  $-3.5$ , the value often assumed for protoplanetary disks. For post-AGB disks the inclusion of large grains is thus clearly very important. Third, our derived dust masses are rather high. In the case of 89 Her, our dust mass is a factor of five larger than the value estimated from the measured gas mass (from CO rotational lines) by Bujarrabal et al. (2013) combined with a standard gas/dust ratio of 100. This we judge to be within the errors of both methods, especially given the different assumed distance. In the case of AC Her, the gas/dust ratio is also a fit parameter in our models because it affects the settling of dust particles and thus the shape of the inner rim, and hence the interferometric data. Our dust mass for this system is a factor  $\sim 3$  larger than the total gas mass that was found by Bujarrabal et al. (2013). With the indication for a gas/dust ratio smaller than 100 (the best-fit value is  $\sim 1$ -10) from our models and our larger distance, this discrepancy is within what the respective errors allow. Nevertheless, it would be interesting to check whether the CO lines are affected by optical depth

effects, to see whether our modeling might be biased by any of our assumptions or simplifications. Only by combining the various data sets can this be resolved. Finally, the foremost distinction between the two systems are their vastly different inner radii. The hottest dust in 89 Her coincides rather well with the expected dust condensation radius. In AC Her the inner rim is located much further out, almost an order of magnitude beyond the dust condensation radius, categorizing it as a “post-AGB transitional disk.” The origin of this large inner hole is yet unexplained. It is interesting that AC Her combines a rather large disk mass with a seemingly evolved inner disk. On the other hand, 89 Her has a relatively massive large-scale outflow, well-resolved in CO rotational lines, despite its inner radius coinciding with the dust condensation radius. Such an outflow is not yet detected in AC Her. Are different disk dispersal mechanisms responsible for the current state of the two systems?

## 5. Conclusions

Optical interferometry is a powerful technique to trace the inner regions of dusty disks. Radiative transfer modeling techniques of optically thick media have come of age in the past decade and can now be successfully applied to the circumbinary disks around post-AGB binaries. Combining these tools allows us to constrain the elusive inner disk regions in great detail. We have shown for two systems that a large set of state-of-the-art observations can be well matched with these models, but that the resulting parameter values raise several questions concerning their evolution.

The works presented here, and even published throughout the literature, have only scratched the surface of what is feasible. With the 2nd-generation instruments coming online on the VLTI in the coming years, and ALMA almost fully operational, more exciting results can be expected in the coming decade. By tracing the complex structures and matter streams in a large number of post-AGB objects, we hope to connect these peculiar systems to specific populations of stars from which they originate and into which they evolve. An exciting time lies ahead!

## References

- Bujarrabal, V., Alcolea, J., Van Winckel, H., Santander-García, M., & Castro-Carrizo, A. 2013, *A&A*, 557, A104. 1307.1975
- Gielen, C., van Winckel, H., Waters, L. B. F. M., Min, M., & Dominik, C. 2007, *A&A*, 475, 629. 0709.3197
- Hillen, M., Menu, J., Van Winckel, H., Min, M., Gielen, C., Wevers, T., Mulders, G. D., Regibo, S., & Verhoelst, T. 2014, *A&A*, 568, A12. 1405.1960
- Hillen, M., Verhoelst, T., Van Winckel, H., Chesneau, O., Hummel, C. A., Monnier, J. D., Farrington, C., Tycner, C., Mourard, D., ten Brummelaar, T., Banerjee, D. P. K., & Zavala, R. T. 2013, *A&A*, 559, A111. 1308.6715
- Kamath, D., Wood, P. R., & Van Winckel, H. 2014, *MNRAS*, 439, 2211. 1402.5954
- Min, M., Dullemond, C. P., Dominik, C., de Koter, A., & Hovenier, J. W. 2009, *A&A*, 497, 155. 0902.3092
- Mulders, G. D., & Dominik, C. 2012, *A&A*, 539, A9. 1201.1453
- Pilbratt, G. L., Riedinger, J. R., Passvogel, T., Crone, G., Doyle, D., Gageur, U., Heras, A. M., Jewell, C., Metcalfe, L., Ott, S., & Schmidt, M. 2010, *A&A*, 518, L1. 1005.5331
- Swinyard, B. M., & et al. 2010, *A&A*, 518, L4. 1005.5073
- van Aarle, E., van Winckel, H., Lloyd Evans, T., Ueta, T., Wood, P. R., & Ginsburg, A. G. 2011, *A&A*, 530, A90. 1104.2254

Van Winckel, H., Waelkens, C., Waters, L. B. F. M., Molster, F. J., Udry, S., & Bakker, E. J. 1998, A&A, 336, L17  
Waters, L. B. F. M., Waelkens, C., Mayor, M., & Trams, N. R. 1993, A&A, 269, 242

## **Discussion**

*Posch:* You mentioned amorphous carbon and iron as continuum opacity sources in your models. How well is the abundance of amorphous carbon or iron constrained by your models? What would happen if you'd set the abundances of Fe and amorphous carbon to zero in your models?

*Hillen:* The abundance of amorphous carbon or metallic iron cannot be constrained with the data and models that we have. Other parameters, like the grain size distribution power law index, can mimic effects of varying opacities/abundances.